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# Search for a low-energy resonance in ${}^7\text{He}$ with the ${}^7\text{Li}(\text{d}, {}^2\text{He})$ reaction <sup>☆</sup>

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## Abstract

A search for the  $J^\pi = 1/2^-$  spin-orbit partner of the  $J^\pi = 3/2^-$  ground state in  ${}^7\text{He}$  has been performed with the  ${}^7\text{Li}(\text{d}, {}^2\text{He})$  charge-exchange reaction. The experimental results are incompatible with recent claims of such a state at very low excitation energy [M. Meister, et al., Phys. Rev. Lett. 88 (2002) 102501]. A decomposition of the spectrum is performed taking into account known resonances and quasifree charge-exchange reactions on  ${}^7\text{Li}$  as well as on triton and  ${}^4\text{He}$  clusters in the  ${}^7\text{Li}$  ground state. A possible resonance at an excitation energy  $E_x \approx 1.45$  MeV with a width  $\Gamma \approx 2.0$  MeV is suggested when the quasifree charge-exchange process on  ${}^7\text{Li}$  is constrained by a measurement of the  ${}^6\text{Li}(\text{d}, {}^2\text{He})$  reaction. Gamow–Teller strengths for transitions to the lowest states in  ${}^7\text{He}$  deduced from the differential cross sections are in remarkable agreement with results from ab initio quantum Monte Carlo calculations.

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The structure of light exotic nuclei is a subject currently at the heart of nuclear physics. Remarkable advances have been made in the theoretical description based on ab initio methods [1,2] as well as experimentally due to the rapid progress in the production of radioactive beams. As an example, thorough investigations of the neutron-rich He isotopes have demonstrated

their dominant  $\alpha$ -cluster structure [3], leading to a two-neutron halo in  ${}^6\text{He}$  and a peculiar  $4n + \alpha$  structure in  ${}^8\text{He}$  while the odd-mass isotopes  ${}^5,7\text{He}$  are particle-unbound.

Recently a controversy arose about the possible observation of a  $1/2^-$  state in  ${}^7\text{He}$  expected in the low-energy region from the  $1p_{1/2}$  single-particle configuration. An investigation of  ${}^6\text{He} + n$  correlations after  ${}^8\text{He}$  breakup at GSI [4] indicated such a state in  ${}^7\text{He}$  at an unusually low excitation energy of  $E_x = 0.57(10)$  MeV with a small width  $\Gamma = 0.75(8)$  MeV. This would imply a dramatic reduction of the spin-orbit force. Studies of isobaric analog states of  ${}^7\text{He}$  in the  ${}^6\text{He}(p, n)$  compound nucleus reaction at Notre Dame [5,6] contradict the finding of Ref. [4] suggesting a broad  $1/2^-$  resonance above  $E_x \simeq 2.3$  MeV (the highest energy accessible in their experiments). However, based on continuum shell-model calculations it has

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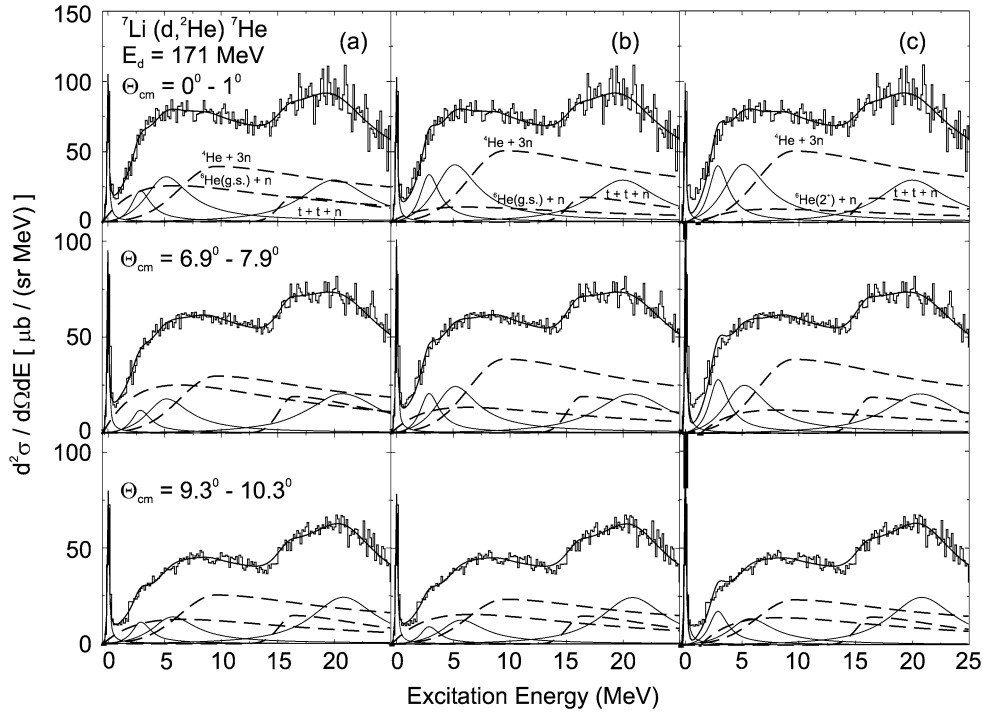


Fig. 1. Selected spectra of the  ${}^7\text{Li}(d, {}^2\text{He}){}^7\text{He}$  reaction at  $E_d = 171$  MeV for different angular bins and their decomposition. Solid lines: Experimentally established low-lying resonances plus resonance at  $E_x \approx 20$  MeV taken from [16] and resulting fit. Long-dashed lines: Background from quasifree scattering on  ${}^7\text{Li}$  ( ${}^6\text{He}(\text{g.s.}) + n$  and  ${}^6\text{He}(2^+) + n$  channels) using the model of Ref. [18], on the  ${}^4\text{He}$  cluster in  ${}^7\text{Li}$  ( $t + t + n$  channel) and on the triton cluster ( ${}^4\text{He} + 3n$  channel) using the data from [21]. (a): relative magnitudes determined by a fit to the data. (b): quasifree scattering on  ${}^7\text{Li}$ , assuming  ${}^6\text{He}(\text{g.s.}) + n$  channel or (c): assuming  ${}^6\text{He}(2^+) + n$  channel, respectively, fixed by a measurement of the  ${}^6\text{Li}(d, {}^2\text{He})$  reaction. See text.

been pointed out by Halderson [7] that a resonance with the parameters of Ref. [4] would probably not be detectable in the particular kinematics chosen in Ref. [5]. The  $p({}^8\text{He}, d)$  study of Skaza et al. [8] on the other hand finds the indication of the low-energy resonance in  ${}^7\text{He}$  with parameters  $E_x = 0.9 \pm 0.5$  MeV,  $\Gamma = 1.0 \pm 0.9$  MeV.

The present Letter provides an alternative access to this important question by utilizing the  ${}^7\text{Li}(d, {}^2\text{He}){}^7\text{He}$  charge-exchange reaction at zero degrees, where Gamow–Teller (GT) transitions are selectively excited. This reaction at intermediate energies has been developed recently as a high-resolution spectroscopic tool for the study of GT strength distributions [9]. Like the  ${}^7\text{He}$  ground state (g.s.), the  $J^\pi = 3/2^-$  g.s. of  ${}^7\text{Li}$  is also interpreted as  $1p_{3/2}$  single-particle state. GT transitions populating spin-orbit partners—like the  $1p_{3/2}$  and  $1p_{1/2}$  states—should have similar strengths. This is also predicted by Green Function Monte Carlo (GFMC) calculations discussed below (see Table 2). Since the g.s. is sufficiently populated in a charge-exchange reaction [10], a low-lying resonance in  ${}^7\text{He}$  with the parameters from Ref. [4] should give a clear signal.

The experiment was performed at the AGOR cyclotron at the KVI Groningen, The Netherlands, using a 171 MeV deuteron beam. The two protons forming the unbound  ${}^2\text{He}$  system were detected with the Big-Bite magnetic spectrometer [11] and the EUROSUPERNOVA detector [12] consisting of two vertical drift chambers in the focal plane and a further tracking detector with a set of four multi-wire proportional chambers. The methods of  ${}^2\text{He}$  identification and data analysis are described in [13].

A self-supporting  ${}^7\text{Li}$  target isotopically enriched to 99.9% with an areal density of  $9 \text{ mg/cm}^2$  was used. Data for energy calibration of the spectra were taken with a  ${}^{12}\text{C}$  target of comparable thickness, which also served for the determination of the experimental energy resolution  $\Delta E \simeq 150$  keV (FWHM). Measurements were made at four different spectrometer angle settings corresponding to a range of center-of-mass angles between  $0^\circ$  and  $11.3^\circ$ . The resulting spectra were further divided into 2 or 3 angular bins of equal size. Beam currents varied between 0.3 and 1.5 nA.

Fig. 1 displays examples of the resulting double-differential cross sections as a function of the resonance energy in  ${}^7\text{He}$  for three angular bins as examples. The g.s. transition is resolved in all spectra. The low threshold energy (besides the already open  ${}^6\text{He}(\text{g.s.}) + n$  channel) for  ${}^4\text{He} + 3n$  decay leads to a broad distribution of strength even at low excitation energies. Two resonances in  ${}^7\text{He}$  at  $E_x = 2.9(1)$  and  $5.8(3)$  MeV with widths  $\Gamma = 1.99(11)$  and  $4(1)$  MeV, respectively, observed in selective reactions [14,15] where they provide a clear signal, are not excited selectively in the present experiment. The prominent structure around  $E_x \approx 20$  MeV was also observed in the  ${}^7\text{Li}(n, p)$  reaction [16] and may result from an excitation of the isovector giant dipole resonance of the  $\alpha$  cluster core in  ${}^7\text{He}$  similar to observations in  ${}^7\text{Li}$  [17].

Inspecting Fig. 1, the identification of a possible additional low-lying resonance is clearly a difficult task. In a first step we attempt a decomposition into a minimum number of Breit–Wigner resonances with an energy-dependent penetrability plus a physical background not only due to the quasifree nucleon

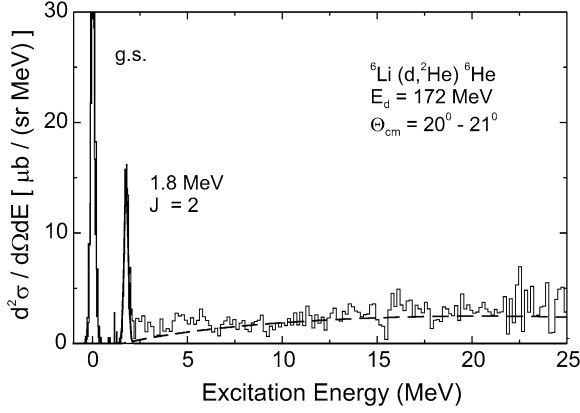


Fig. 2. Spectrum of the  ${}^6\text{Li}(d, {}^2\text{He}) {}^6\text{He}$  reaction at  $E_d = 171$  MeV and  $\Theta_{\text{cm}} = 20^\circ - 21^\circ$  (from an analysis of Ref. [19]). The long-dashed line is a fit of a semi-phenomenological model [18] for the quasifree scattering cross section.

knockout from  ${}^7\text{Li}$ , but also due to the charge-exchange reactions on  $t$  and  ${}^4\text{He}$  because of the pronounced cluster structure of the  ${}^7\text{Li}$  ground state with a  $({}^4\text{He} \otimes t)$  configuration. For the quasifree scattering on  ${}^7\text{Li}$  as a whole there exists not only a distribution for the  ${}^6\text{He}$  ground state, but also for the first excited  $2^+$  state. The excitation energy dependence of both processes ( ${}^6\text{He}(\text{g.s.}) + n$  and  ${}^6\text{He}(2^+) + n$  channels) is described by the semi-phenomenological parameterization of Erell et al. [18], which has been applied successfully to intermediate-energy charge-exchange reaction spectra. It is given by

$$\frac{d^2\sigma}{d\Omega dE} = N \frac{1 - \exp\left(\frac{E - E_0}{T}\right)}{1 + \left[\frac{E - E_{\text{QF}}}{W_L}\right]^2}, \quad (1)$$

where  $E$ ,  $E_{\text{QF}}$  and  $E_0$  denote the outgoing  ${}^2\text{He}$  energy, the maximum of the quasifree peak approximated by a Lorentz function and a cutoff energy due to Pauli blocking, respectively. The quasifree peak energy is determined from the comparison of the quasifree  $(d, {}^2\text{He})$  reaction on the target with the analogous elementary reaction on the proton

$$E_{\text{QF}} = E({}^1\text{H}) - S_n. \quad (2)$$

Here,  $E$  denotes the kinetic energy of the  ${}^2\text{He}$  particles for the  ${}^1\text{H}(d, {}^2\text{He})$  reaction and  $S_n$  the neutron separation energy. The Lorentzian width depends on the momentum transfer  $q$

$$W_L = W_{L_0} \left[ 1 + \alpha \left( \frac{q}{k_F} \right)^2 \right]. \quad (3)$$

The scaling parameter  $T = 4.0$  MeV and the parameters  $W_{L_0} = 16.26$  MeV,  $\alpha/k_F^2 = 0.363 \text{ fm}^{-2}$  from Eq. (3) were determined by a measurement of the  ${}^6\text{Li}(d, {}^2\text{He}) {}^6\text{He}$  reaction [19] under the same kinematical conditions as the present experiment at large scattering angles, where the quasifree cross section should dominate. It may be noted, that the results obtained independently at different momentum transfers indicate, that the normalization factor  $N$  is  $q$ -independent. This is also consistent with findings of Wang et al. [20] for quasifree cross sections in the  $(p, n)$  reaction on  $p$ -shell nuclei. As demonstrated in Fig. 2 for the example of the angular bin  $\Theta_{\text{cm}} = 20^\circ - 21^\circ$ , the approach of [18] provides a good description  ${}^6\text{Li}(d, {}^2\text{He}) {}^6\text{He}$

Table 1

Angle-dependent parameters for the quasifree background parametrization of Eq. (1)

$\Theta_{\text{cm}}$	$q \text{ (fm}^{-1}\text{)}$	$W_L \text{ (MeV)}$	$E_{\text{QF}} \text{ (MeV)}$	$E_0 \text{ (MeV)}$
$0^\circ - 1^\circ$	0.039	16.27	168.744	158.719
$6.9^\circ - 7.9^\circ$	0.409	17.25	165.313	158.244
$9.3^\circ - 10.3^\circ$	0.541	17.99	162.721	157.886

data. Angle-dependent parameters of Eq. (1) for the kinematics displayed in Fig. 1 are listed in Table 1. Relativistic kinematics was used for the calculations.

To describe the energy dependence of the charge-exchange reactions on the cluster components we use data on the  ${}^3, {}^4\text{He}(p, n)$  reactions [21] at momentum transfers comparable to our case. The corresponding thresholds are  $E_x = 0.53$  MeV and  $E_x = 11.87$  MeV for the  ${}^4\text{He} + 3n$  and  $t + t + n$  channels, respectively. In order to apply the  $(p, n)$  results [21] for the  $(n, p)$  reactions on the  ${}^7\text{Li}$  g.s. clusters, one can employ charge symmetry. Furthermore,  ${}^3\text{He}(p, n)3p$  represents the mirror reaction to the required  $t(n, p)3n$  channel.

Returning to the  ${}^7\text{Li}(d, {}^2\text{He}) {}^7\text{He}$  data, three different analyses of the spectra are presented in the following. The fits take into account the known resonances [14,15] at low excitation energies (g.s., 2.9 and 5.8 MeV). Their centroids and widths are allowed to vary within the experimental uncertainties [22]. Additionally, the prominent bump at  $E_x \approx 20$  MeV is described as a single resonance with the parameters deduced by [16]. Furthermore, the three quasifree background channels discussed above are included. Good overall description of the data can be achieved (cf. Fig. 1). Clearly, independent of detailed assumptions about the centroid energies and widths of possible resonances at higher excitation energies, the decompositions shown in Fig. 1 demonstrate that they do not contribute significantly to the cross sections in the low-energy region. The same is true for background processes like the  ${}^4\text{He} + 3n$  and  $t + t + n$  channels, which are structureless in the region of interest and slowly and smoothly increasing having maxima at much higher energies.

On the other hand, the magnitude of the quasifree  ${}^6\text{He} + n$  contribution is the most critical aspect in the analysis of the  ${}^7\text{He}$  spectra. In Fig. 1(a), a decomposition of the spectra is shown where the overall normalization  $N$  from Eq. (1) for both the  ${}^6\text{He}(\text{g.s.}) + n$  and  ${}^6\text{He}(2^+) + n$  channels is treated as a free parameter during the fit. However, the  ${}^6\text{He}(2^+) + n$  part with a threshold energy  $E_x = 1.35$  MeV is predicted to be zero in the free fit. Moreover, the resulting differential cross section angular distribution of the  ${}^6\text{He}(\text{g.s.}) + n$  channel shows considerable scattering and, in particular, a strong decrease at larger momentum transfers incompatible with the physical interpretation of a quasifree knockout process. Therefore, in an alternative analysis (Fig. 1(b), (c)) we assume that the magnitude of the single nucleon knockout quasifree cross section is not changing significantly when going from  ${}^6\text{Li}$  to  ${}^7\text{Li}$  and therefore the overall normalization  $N$  in Eq. (1) can be taken from the corresponding  ${}^6\text{Li}(d, {}^2\text{He}) {}^6\text{He}$  data [19]. We consider two extreme cases: the total  ${}^6\text{He} + n$  contribution is described exclusively by the

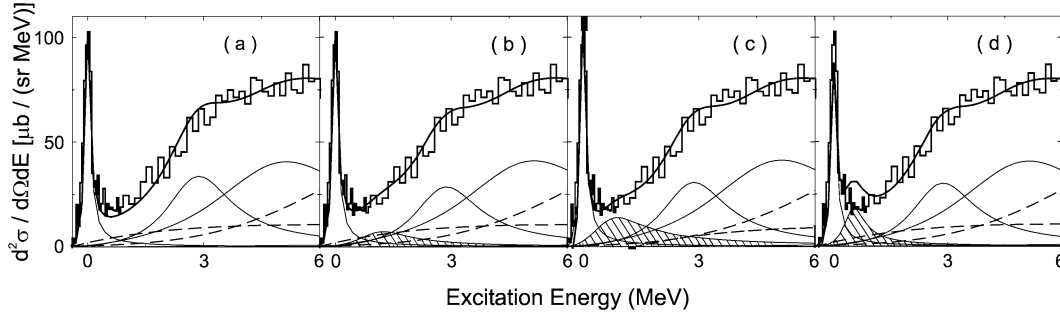


Fig. 3. Low-energy region of the  ${}^7\text{He}$  spectrum obtained for  $\Theta_{\text{cm}} = 0^\circ\text{--}1^\circ$  (top row of Fig. 1). (a), (b) and (d): solid and dashed lines are the same as in Fig. 1(b). Hatched area in (b): additional low-energy resonance, which gives the best fit of the data and (d): additional resonance assuming the parameters of Ref. [4]. (c): solid and dashed lines are the same as in decomposition (c) of Fig. 1. Hatched area in (c): additional low-energy resonance necessary to describe the data.

${}^6\text{He}(\text{g.s.}) + n$  channel (Fig. 1(b)) or by the  ${}^6\text{He}(2^+) + n$  channel (Fig. 1(c)).

An extended view of the low-energy part of the  $\Theta_{\text{cm}} = 0^\circ\text{--}1^\circ$  spectrum with the decomposition presented in Fig. 1(b) is plotted in Fig. 3(a). The g.s. resonance and the region  $E_x \geq 3$  MeV are well described. However, in between the data overshoot the fit, indicating the presence of a possible further resonance. Indeed, this is not only observed at  $0^\circ$  but also in the other spectra, except for the largest scattering angles measured. On the other hand, inclusion of an additional resonance with  $E_x \simeq 1.45$  MeV and  $\Gamma \simeq 2$  MeV provides an excellent description of the data, see Fig. 3(b). Considering the decomposition from Fig. 1(c), the resonance becomes even more pronounced, see Fig. 3(c). For both cases the corresponding  $\chi^2/\text{d.o.f.}$  improves from 2.3 to about 1.7. Assuming alternatively an additional resonance with the parameters of Ref. [4] and estimating the cross section at  $0^\circ$  from the predictions of the ab initio calculations discussed below leads to the poor fit shown in Fig. 3(d). Evidently, such a resonance should be clearly visible in the data.

The estimated uncertainties for the centroid energy and the resulting width of a possible additional resonance at low  $E_x$  are rather large, in particular, due to the large error of the 5.8 MeV resonance width. A range of acceptable values  $E_x = (1.45^{+0.7}_{-0.5})$  MeV,  $\Gamma = (2.0^{+1.0}_{-1.1})$  MeV was determined by the uncertainty of the theoretical  $\chi^2$  distribution. Systematic uncertainties of the extracted resonance parameters due to absolute normalization of the data and acceptance corrections [13] are of the order of 15%.

A further test of the possible evidence for a low-lying resonance in  ${}^7\text{He}$  with the properties extracted from the data is provided by a comparison of GT strengths extracted from the measured charge-exchange cross sections with GFMC calculations [1]. These ab initio calculations provide a remarkably successful description of the properties of light nuclei including the transition from stable nuclei to the proton and neutron drip lines. They also reproduce a large single-particle spectroscopic factor of the  ${}^7\text{He}$  g.s. as deduced from a  $R$ -matrix analysis of the present data [23]. Calculations for  ${}^7\text{Li} \rightarrow {}^7\text{He}$  GT transitions are available [24] using a variational Monte Carlo (VMC) approach, which precisely reproduces weak decay properties in  $A = 6, 7$  nuclei [25]. The predictions are shown on the l.h.s. of Table 2.

Table 2

Comparison of VMC model predictions and experimental excitation energies and GT transition strengths populating the lowest resonances in  ${}^7\text{He}$

$J^\pi$	VMC model		Experiment	
	$E_x$ (MeV)	B(GT)	$E_x$ (MeV)	B(GT)
$3/2^-$	0.0	0.0039(1)	0.0	0.0044(14)
$1/2^-$	2.9(3)	0.0055(1)	$1.45^{+0.7}_{-0.5}$	0.0076(23) <sup>a</sup>
$5/2^-$	3.4(1)	0.0110(2)	2.9(1)	0.0252(78)

<sup>a</sup> A spectroscopic factor ratio of 1:3 [31] is assumed for the population of the  ${}^6\text{He}(\text{g.s.}) + n$  and  ${}^6\text{He}(2^+) + n$  channels.

The extraction of B(GT) strengths from the experimental (d,  ${}^2\text{He}$ ) results is based on the proportionality of B(GT) to the  $\Delta L = 0$  part of the charge-exchange cross sections at momentum transfer  $q = 0$  [26], extracted from an extrapolation of the measured angular distributions. An empirical normalization factor for the (d,  ${}^2\text{He}$ ) reaction derived from data on  $p$ - and  $sd$ -shell nuclei [27] is used for the determination of the B(GT) strengths. The same factor is adopted in the present analysis allowing for a systematic error of 15%. The angular distributions of the  ${}^7\text{Li}(\text{d}, {}^2\text{He})$  reaction populating low-lying states in  ${}^7\text{He}$  are displayed in Fig. 4. The data exhibit a quite unexpected behavior: while angular distributions of prominent GT transitions in charge-exchange reactions are normally strongly peaked at  $\Theta_{\text{cm}} = 0^\circ$ , only a weak angle dependence is visible in Fig. 4. In particular, the g.s. cross section angular distribution is almost constant.

Theoretical predictions are obtained from distorted wave Born approximation (DWBA) calculations employing the code ACCBA [28], using shell-model wave functions (ab initio wave functions are still not available) to describe the initial and final states and the Love–Franey effective projectile-target interaction [29]. The flatness of the angular distributions indicates significant  $\Delta L > 0$  contributions, which may arise from the tensor part of the effective interaction or the d-wave component of the deuteron ground state. The cross sections at angles close to  $0^\circ$  are comparatively small, about 70 times weaker than the well-known  $p_{3/2} \rightarrow p_{1/2}$  GT transition populated in the  ${}^{12}\text{C}(\text{d}, {}^2\text{He}){}^{12}\text{B}$  reaction at a comparable incident energy [30]. This strong reduction is caused by the dominant cluster structure of the involved nuclei (cf. the VMC predictions in Table 2).



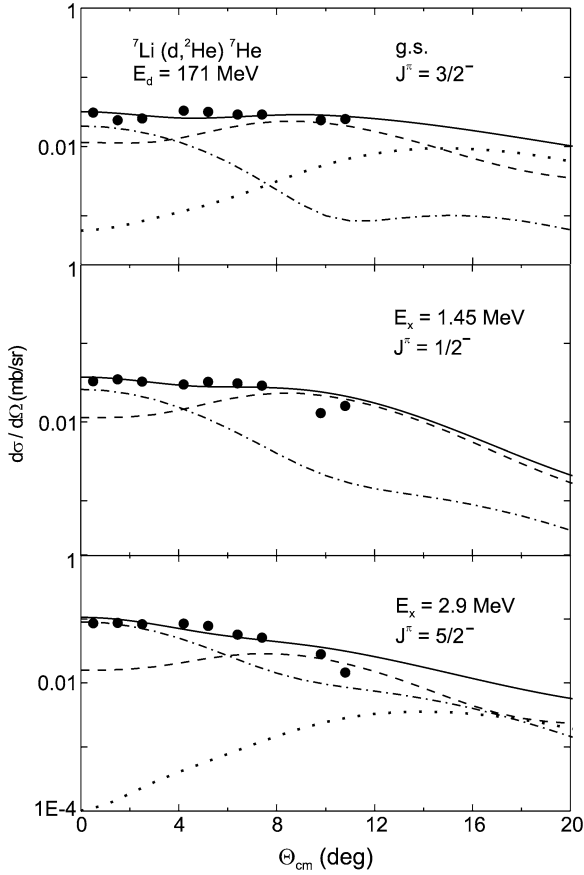


Fig. 4. Experimental angular distributions of the transitions to the levels at  $E_x = 0.0, 1.45$  and  $2.9$  MeV in  ${}^7\text{He}$  (full circles, error bars are statistical only) and DWBA calculations (solid lines) using shell-model wave functions and the Love–Francy effective projectile-target interaction [29]. The dashed-dotted, dashed and dotted lines show the decomposition into  $\Delta L = 0, 2$ , and  $4$  contributions.

In order to separate the  $\Delta L = 0$  and  $\Delta L > 0$  pieces of the  $(d, {}^2\text{He})$  cross sections we performed a systematic study testing a variety of  $p$ -shell residual interactions. The predicted GT transition strengths and thus the corresponding charge-exchange cross sections differ widely, but for a given transition the shapes of the partial  $\Delta L = 0, 2, 4$  DWBA angular distributions are rather insensitive to the particular choice of the interaction. Thus, the decomposition of the cross sections is determined by a fit allowing separate variation of averaged  $\Delta L = 0, 2, 4$  angular distributions. Then the experimental data can be described well and the  $\Delta L = 0$  fraction at  $\Theta_{\text{cm}} = 0^\circ$  amounts to 62%, 68% and 85% for the levels at  $E_x = 0.0, 1.45$  and  $2.9$  MeV, respectively. Results obtained using any of the interactions individually agree within 5%. We have also investigated the impact of a reduced isovector tensor force as suggested in [30]. Again, the resulting  $\Delta L = 0$  cross sections vary less than 5%.

The deduced  $B(\text{GT})$  values are summarized in the r.h.s of Table 2. The experimental uncertainties include statistical and systematic errors from the unit cross section normalization and the model dependence of the DWBA analysis. The experimental  $B(\text{GT})$  value for the  $J^\pi = 1/2^-$  state corresponds to a spectroscopic factor ratio of 1:3 for the quasifree  ${}^6\text{He}(\text{g.s.}) + n$

and  ${}^6\text{He}(2^+) + n$  channels taken from a shell-model prediction [31]. Going from one extreme (only  ${}^6\text{He}(\text{g.s.}) + n$ ) to the other (only  ${}^6\text{He}(2^+) + n$ ), the  $B(\text{GT})$  strength changes from 0.0056 to 0.0084. The weakness of the GT transitions may raise some doubts about the applicability of the proportionality assumption between  $\beta$  decay matrix elements and  $0^\circ$  charge-exchange cross sections [32]. However, the comparison with the VMC predictions in Table 2 demonstrates a remarkable agreement between experiment and theory, not only for the ratio of the possible spin-orbit partners but also for the absolute values.

Finally, we briefly dwell upon the comparison of experimental and theoretically predicted excitation energies for the low-energy resonances in  ${}^7\text{He}$ . The excitation energy of the  $1/2^-$  state depends sensitively on the inclusion of a three-body interaction. The VMC calculation gives  $E_x = 2.0$  MeV. Results for various combinations of two- and three-body interactions are presented in Table XII of Ref. [33] allowing for a range of  $E_x$  values between 0.4 and 3.2 MeV. The combination of the Argonne v18 nucleon–nucleon and Illinois-2 three-nucleon interaction generally gives the best overall agreement for light nuclei [34] and the corresponding values are included in Table 2. The prediction for the  $1/2^-$  state is about 1.5 MeV higher than the experimental finding. Of course, if the  $1/2^-$  state had an excitation energy close to the resonance at  $E_x = 2.9$  MeV these could not be separated in the present experiment but the excess of cross section at low energies would remain unexplained.

To summarize, we have performed a search for the  $p_{1/2}$  spin-orbit partner of the  ${}^7\text{He}$  ground state utilizing the properties of GT transitions selectively excited in the  ${}^7\text{Li}(d, {}^2\text{He}){}^7\text{He}$  charge-exchange reaction at zero degrees. The data do not support a narrow  $1/2^-$  resonance at  $E_x = 0.56(10)$  MeV as claimed by Meister et al. [4], in agreement with the conclusions of Refs. [5, 6]. However, contrary to [5] our results suggest a resonance with parameters  $E_x = (1.45^{+0.7}_{-0.5})$  MeV,  $\Gamma = (2.0^{+1.0}_{-1.1})$  MeV partially overlapping with the range of possible parameters deduced in [6] and as well as those in [8]. As discussed in detail this finding depends sensitively on the modelling of the  ${}^6\text{He} + n$  quasifree scattering contribution to the spectra. The choice of the parameterization [18] is justified by the good description of an analogous measurement of the  ${}^6\text{Li}(d, {}^2\text{He}){}^6\text{He}$  reaction in a kinematical regime where the quasifree cross sections dominate.

The  $B(\text{GT})$  strengths to the lowest states in  ${}^7\text{He}$ , extracted from the  $0^\circ$  cross sections after a decomposition of the spectra including this additional resonance, are in excellent agreement with Quantum Monte Carlo calculations. Further tests of these results may be provided by studies employing the  $(d, p)$  reaction with a radioactive  ${}^6\text{He}$  beam [35,36]. Also, alternative theoretical approaches like the Gamow shell model [37] or fermionic molecular dynamics [38] may help to clarify the question of the  $p$ -shell spin–orbit splitting in  ${}^7\text{He}$ .

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